CHAPTER 3

Materials Technology

The metalcasting industry of the future will be revolutionized by new materials as metallurgical breakthroughs lead to the development of new materials that are more manufacturable and environmentally friendly. The quality and availability of property and performance data about these materials, as well as the cost and availability of the materials themselves, will help determine how competitive metalcasters will be in the rapidly transforming international markets of the future.

Current Situation

More than 80% by weight of all castings produced in U.S. foundries are ferrous castings. Gray iron castings represented about 43% by weight of all U.S. casting shipments in 1995. Exhibit 3-1 shows the distribution according to metal of the total 14.4 million tons of casting shipments in 1995. The distribution of the total U.S. metalcasting industry value of shipments of $23 billion in 1994 is shown by metal in Exhibit 3-2.

Exhibit 3-1. Casting Shipments by Metal - 1995

Metal	Shipments (000 tons)	Percentage of Total
Gray Iron	6,251	43.4
Ductile Iron	4,027	27.9
Malleable Iron	249	1.7
Steel	1,470	10.2
Aluminum	1,652	11.4
Copper-Base	311	2.2
Zinc	394	2.7
Magnesium	31	0.2
Other Non-Ferrous	43	0.3
TOTAL	**14,428**	**100.0**

Source: *1997 Metalcasting Forecast & Trends*, The American Foundrymen's Society, 1996.

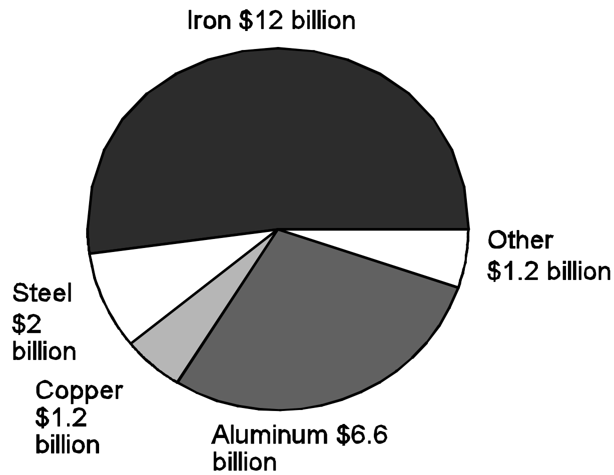
Cast metal components compete with polymer and ceramic materials in most product markets. These non-metallic materials (including composites) have challenged castings in established markets and shut them out of some emerging markets.

Trends and Drivers

The trends and driving issues related to the development, adoption, and use of new and improved materials for castings are centered on materials properties and material requirements.

Increased availability of data on **material and design properties** has increased the designer's ability to use castings. The development of a solid base of technical knowledge is helping U.S. metalcasters improve existing products and develop new applications in order to compete with alternative materials and metal-forming techniques as well as foreign castings. The enhancement of this knowledge base with additional performance data, together with its incorporation into design tools and the definition of materials standards, will increase user confidence and help castings penetrate new markets.

Exhibit 3-2. Value of U.S. Castings Shipped by Metal (1994)



In spite of the increases in available data on the mechanical, physical, performance, and design properties of materials and castings, many problems remain. For example, there is wide variation in the data and no single source of information exists. Gaps exist in the knowledge of the performance of standard steel, copper-based, and aluminum alloys; casting processes; and heat-treating processes.

An increase in the number of casting applications will lead to higher demands for **new materials** that are stronger, lighter, more reliable, and more manufacturable. Stronger and lighter-weight cast metal alloys will be needed to be able to compete better with composites in new engineered structural applications. The accelerating demands of technology will require metalcasters to place more emphasis on new materials processing techniques. New composites, ceramics, plastics, and other materials will be used in addition to metals.

Aluminum and magnesium castings with corrosion-inhibiting properties and high-quality ductile iron castings (with tighter tolerance and controlled microstructures/mechanical properties) are predicted to be increasingly in demand in the aerospace, electrical machinery, and automotive markets. There will also be increased demand for high-alloy steel castings that are heat-resistant for use in valve, pump, furnace, and turbine applications.

Environmental and health concerns have created a need to find an appropriate substitute for lead in the copper-based alloys, brass and bronze. Environmental and health concerns also have created a need to extend refractory life.

Consumable material suppliers are relied on by metalcasters to lead the way in developing materials that will produce higher quality castings with a minimum environmental impact. Improved materials for patterns and dies can reduce casting costs while increasing quality. Die life has a major impact on the production cost of die cast components, with the cost of the die contributing an estimated 10% or more of the cost of a die casting.

Performance Targets

The industry's vision, *Beyond 2000*, describes the metalcasting industry's goal in materials technology as follows:

> " improving the variety, integrity, and performance of cast metal products"

The industry has provided some insight into the factors influencing variety, integrity, and performance. The term "variety" as it applies to the performance target is assumed to refer to material flexibility. This includes both the availability of materials with specific properties and the standardization of materials to provide complete chemistry/property/performance data. Integrity includes factors such as porosity (and other melting and solidification discontinuities) and consistency, while performance is assumed to refer to product reliability and lifetime.

Desired improvements in variety, integrity, and performance are not able to be quantified because of the application-specific nature of these three attributes. Improvements would have to be based on baseline data, which differ for every alloy and every application.

Casting quality and consistency issues (which are related to integrity and performance of cast metal products) are discussed in Section 4, Manufacturing Technologies.

Technology Barriers

The barriers to realizing Materials Technology goals in the metalcasting industry are related to

- knowledge of material properties,
- availability of processing techniques,
- liquid metal and cast product quality,
- availability of new materials, and
- communication and institutional issues within the industry and between the industry and its customers.

As shown in Exhibit 3-3, the majority of technology barriers are related to material properties.

The single most critical barrier to improving the variety, integrity, and performance of castings is the lack of fundamental knowledge on **material properties**. Metalcasters agree that a major problem in their industry is the inability of designers to do an effective job because of:

- a lack of fundamental knowledge of material properties as a function of chemistries and casting route (i.e., how each casting process affects properties)
- a lack of knowledge of the interrelationships of various elements on casting performance (especially true for non-ferrous alloys)
- the lack of a common knowledge base on materials physical property data (especially for aluminum and magnesium but also for iron), casting design, and performance

For some alloys, the published property data are were developed 50 years ago or longer and may no longer be applicable to current metalcasting processes. On the other hand, the data may have gaps that force the designer to abandon a particular alloy or process. A related barrier is the inability to predict

Exhibit 3-3. Major Technology Barriers in Materials
(Most Critical Barriers Boldfaced)

AREA	BARRIERS
Material Properties	**Lack of fundamental knowledge of material properties as a function of chemistry and casting route** - lack of coordinated focus on doing this **Lack of actual operating data for use in simulation and modeling for properties** Designers do not really understand environment of product or properties they need Lack of property data Lack of guaranteed minimum properties for designers Inability to define maximum feature allowed (e.g., defect, morphology, porosity inclusion) and how it influences material properties - actual characteristic of morphology may not be entered in Databases of published test results do not include the specifics of what is being tested - strength-controlling mechanisms - technology transfer problems Variation among tests is an international problem - cannot afford to do all tests required - engineers do not know enough to determine which tests to specify - lack of agreement on standard tests Lack of non-destructive inspection techniques for castings Current radiography standards do not reveal enough to give casting designers appropriate guarantees for their designs Development of consistent properties in cast components has been difficult because of wide variation in chemistry requirements, effects of process parameters, and specific casting features
Processing	**Lack of methods to cast clean metals (alloy cleanliness is acceptable but then problems occur after melting and pouring)** **Inability to control the introduction of deleterious elements (Sb, P, S...) from recycled metals** - no method to control or analyze **Lack of knowledge on process-microstructure-chemistry-property interactions** **Lack of clean metals technology (undesired elements or inclusions)** Inability to melt/cast in-situ (like plastics molding) Lack of techniques for assessing liquid metal composition prior to casting Lack of convenient tools to measure stress level and die-surface hardness of casting dies Guidelines and techniques for removing the damaged surface layer produced during electric discharge machining (EDM) are insufficient

Exhibit 3-3. Major Technology Barriers in Materials (Most Critical Barriers Boldfaced)	
AREA	**BARRIERS**
Quality	**Lack of accurate, fast, reliable, and non-destructive methods to quantify casting defects** Quality problems with every kind of material
New Materials	**Lack of low-cost composite materials** Difficulty incorporating new materials into the industry (standards, industry mind-set) Lack of new stronger and lighter weight cast metal alloys hurts the ability of castings to compete with composite materials for certain structural components Many new alloys do not appear in any national standard or construction code Few alternatives to H-13 steel for making dies
Communication/ Institutional	Inability to get production intent for new materials from users Too much emphasis on cost-containment Casters do not understand what design engineer needs in terms of testing Lack of communication with designers - assessment of designers' needs

and describe how features such as level of inclusions, porosity, or morphology will influence material properties.

Several barriers in the material properties category are related to testing and the publication of test results. Current testing methods determine chemistries based on the metal before it is cast. Tensile properties are determined by separately cast test bars. However, alloy chemistries and properties can be slightly altered during casting, while cooling rates will alter tensile properties.

The variation among the different kinds of tests used in the industry is considered an international problem. Published test results typically do not include the specifics of what is being tested, limiting the usefulness of the data. The lack of agreement among metalcasters on standardization of testing is complicated by the inability of most metalcasters to afford all of the tests required to fully characterize a casting, and the lack of knowledge on the part of designers to determine which tests should be specified. Designers typically do not really understand the environment of the product or the product properties needed.

The lack of comprehensive, standardized data also limits the effectiveness of available simulation and modeling tools. The value of using process simulation tools to predict casting properties could be greatly enhanced if input data based on the actual operating environment were used.

The **melting and casting processes** currently used also present barriers to improving the performance and integrity of castings. Many of the barriers arise from the limitations current processes present in casting cleanliness. The industry as a whole has difficulty in preparing clean metals because of undesired elements and inclusions. Some of these undesired elements (e.g., antimony, phosphorus, sulfur) are introduced from recycled metal. Metalcasters are unable to control or even analyze such contaminants. Techniques for assessing and controlling the composition of liquid metal prior to casting are lacking in general. In addition to a lack of methods for cleanly casting metals, the inability to melt and cast metal in-situ (like plastics molding) is considered a barrier to metal integrity. Metal conveying and pouring operations can adversely affect cleanliness and quality.

A barrier that cuts across both the processing and material properties areas is the lack of information on the effect of casting processes and casting microstructure, chemistry, and properties. The interaction between these variables is key to controlling the quality and performance of cast products.

Quality issues are critical with every kind of metal currently cast, although the severity of the problem may vary with the size and resources of the foundry. Many quality issues are related to the ability to cast clean metals (described above). The lack of accurate, fast, reliable, in-line, and non-destructive methods for quantifying casting defects restricts metalcasters' ability to identify and correct operational problems in a timely manner.

The barriers associated with **new casting materials** encompass both technical and market/institutional issues that affect the availability and adoption of new materials by the metalcasting industry. For example, there is a lack of low-cost composite materials; unless such materials can be made cost-competitive, they cannot substantially penetrate the market. An industry-wide institutional problem is the difficulty that is typically encountered when incorporating new materials into existing applications.

Many of the barriers already discussed in other categories have **communication or institutional** components—the lack of agreement on test standardization, for example. Many barriers in this area are associated with the communications between the metalcaster and the designer. For example, some designers lack an understanding of what is required to make a reliable product and cannot convey what they really need to metalcasters. This lack of communication leads to inadequate assessment of designers' needs. One of the barriers mentioned in the material properties category—lack of understanding on the part of the designer about the properties needed for a product given its expected environment—is directly related to these communication barriers. Other barriers in this area include the industry's emphasis on cost-containment and the inability to get production intent for new materials from potential users.

Research Needs

A wide range of research and development is needed to overcome existing barriers to achieving the metalcasting industry's materials technology goals. Recommended R&D activities are depicted in Exhibit 3-4 by subject category and the expected time frame (near, mid, or long) for completion of the research. Exhibit 3-5 shows the relationships of some key research needs organized to show the relative timing of the R&D efforts by time period.

Research and development needs in the area of **material properties** are considered by industry to be the highest priority needs in materials technology. Specifically, the development of quantitative relationships between alloy chemistries and properties and the various casting processes used is deemed critical to advancing the integrity and performance of castings. Included in this activity would be the creation of a statistically significant property/process database. This R&D could be completed in the mid term (next 3 to 10 years).

A significant number of materials property R&D activities could be completed in the near term. This is particularly true of R&D needs that are more institutional than technical in nature. For example, standard methodologies for material testing should be established in order to reduce the variability of reported test results. In addition, because test specimens vary in size, the results of tests of cast properties should be

Exhibit 3-4. R&D Needs in Materials Technology by Time Frame
(k = Top Priority; M = High Priority; F = Medium Priority)

Time Frame	Material Properties	Processing	Quality	New Materials	Institutional
NEAR (0-3 Years)	**k** Establish standard methods for materials testing **M** Determine effect of inclusion and porosity content on alloy performance **M** Establish techniques for data as input to simulation models, especially heat transfer coefficient - prioritize properties most important to industry for modeling/ marketing verification **F** Determine alloy requirements (compositions) for thin-wall castings that have certain properties Correlate cast property results for various size test specimens Determine castability and cast properties of new wrought alloy chemistries Characterize existing non-metallic pattern materials in terms of wear/abrasion		**M** Assess current techniques available for melt quality and its relationship to part quality Develop improved processes for characterization of porosity defects	**M** Look at novel alloys (e.g., rare earth elements in aluminum alloys) and their effect on ductility and strength	**M** Develop a national initiative to foster interest in materials science and engineering **F** Create web-based material interaction databases; make other data readily available to interested parties Facilitate communication among industrial partners via teleconference, Internet, and other means Suggest to AFS to consider hiring an expert designer(s) Perform market study of designers' needs

Exhibit 3-4. R&D Needs in Materials Technology by Time Frame (k = Top Priority; M = High Priority; F = Medium Priority)					
Time Frame	**Material Properties**	**Processing**	**Quality**	**New Materials**	**Institutional**
MID (3-10 Years)	k Develop quantitative relationships between alloy chemistries, properties, and processing (data-driven) - testing at the limits rather than just the nominal (explore extremes of ranges) to get statistical distribution - property/process database M Develop models that allow modeling from a chemistry standpoint - identify gaps to piece together different types of modeling Determine the effects of casting defects and impurities on degradation of properties Quantify the effects of primary alloying elements and tramp elements on existing pattern shapes	k Develop a clean melting and remelting process M Develop melting/casting processes that minimize the processing steps and minimizes chemistry variations - continuous melting process M Examine emerging technologies (e.g., semi-solids) - assess material properties and how to control them M Develop methods to melt and cast in-situ	M Improve techniques to measure the acceptability of liquid metal prior to casting M Develop creative and innovative techniques for NDE/testing Desensitize alloys to secondary/ unwanted elements (stay in recycling stream)	Develop corrosion- and creep-resistant magnesium alloys Develop lighter weight casting alloys Develop alloys and composites that will facilitate producing stronger and thinner-wall castings Develop alloys and composites with better mechanical, chemical, or physical properties Develop lower-cost, process-insensitive alloys Develop new non-metallic pattern materials Develop improved dies - new die materials - better coatings Develop improved coatings, binders, refractories, and sand	

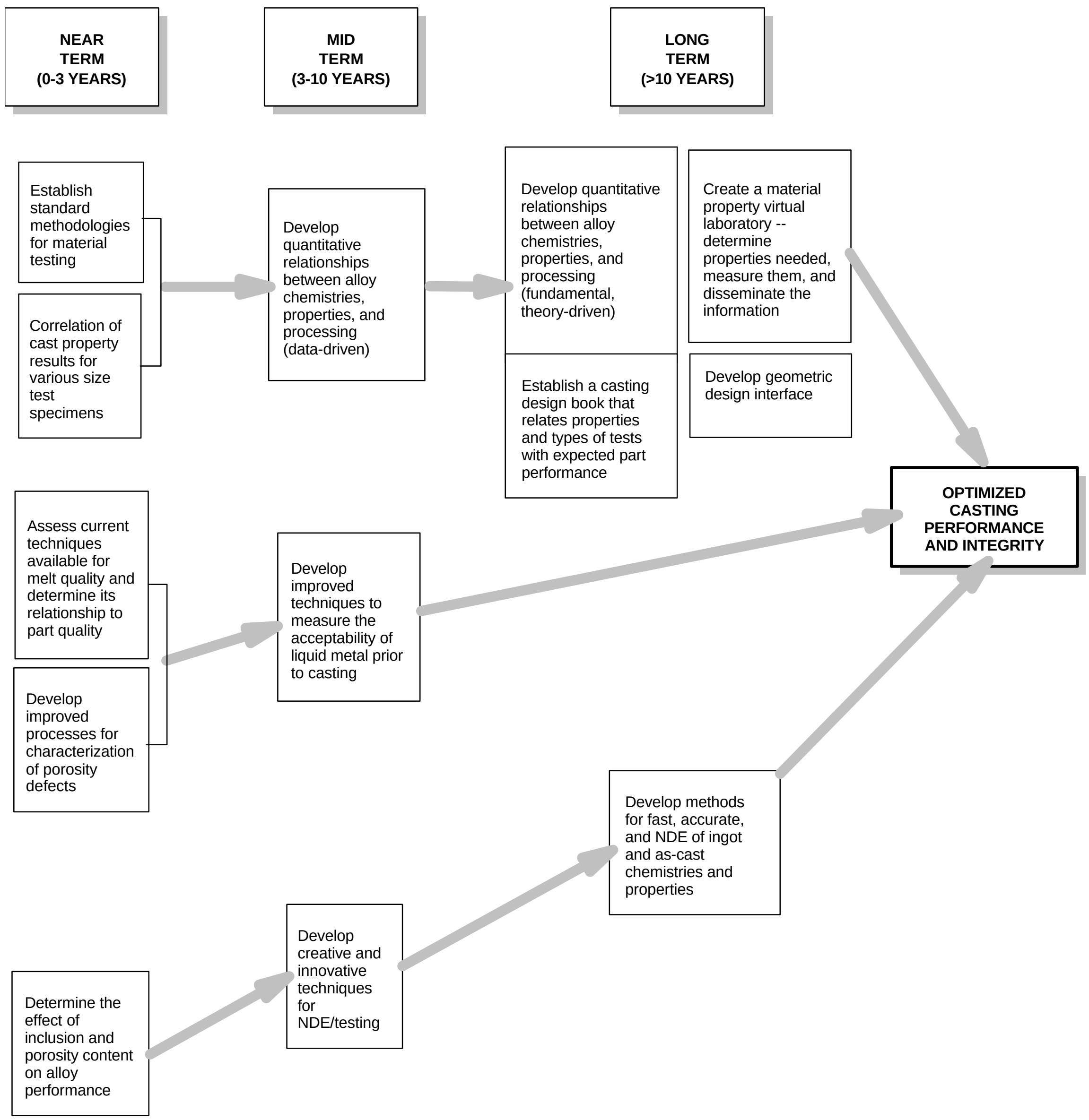
Exhibit 3-4. R&D Needs in Materials Technology by Time Frame (k = Top Priority; M = High Priority; F = Medium Priority)					
Time Frame	**Material Properties**	**Processing**	**Quality**	**New Materials**	**Institutional**
LONG (>10 Years)	**F** Establish a casting design book that relates properties and types of tests to expected part performance **F** Develop a material property virtual laboratory to determine the materials properties needed; measure these properties and disseminate the information Create a design interface for use in geometric design for selecting material (stresses, strains, fatigue, modulus) Develop quantitative relationships between alloy chemistries, properties and processing (fundamental, high risk, theory-driven)	**M** Develop property-driven, designer-oriented foundry processes	**M** Develop methods for fast, accurate, and non-destructive evaluation (NDE) of ingot and as-cast chemistries and properties - melt losses	Develop low-cost and castable composites - uniquely engineered for wear-resistance, stiffness, or other property - iron and aluminum composites Develop new materials that have properties comparable to composites	

correlated according to specimen size. Finally, techniques should be established for obtaining data for use as input to simulation models. The industry must set priorities on which properties and variables it considers most important for modeling and verification.

A more technical near-term need considered high priority by the industry is the determination of the effect of inclusion and porosity content on alloy performance. Other near-term technical needs include the determination of castability and cast properties of new wrought alloy chemistries, and the determination of alloy requirements for thin-wall castings (i.e., what alloy compositions will yield castings with the needed properties).

The most critical mid-term **material property** R&D need —the development of quantitative relationships between alloy chemistries, properties, and processing—is divided into two separate R&D needs. These needs are essentially the same except that the first is "data-driven," meaning that it is based on existing, available information. The second need is considered long-term because it is "theory-driven" and will include new data developed on virtually every element in the periodic table of elements.

Exhibit 3-5. Sequence of Key Materials R&D



A property/process data base will be developed based in part on the relationships developed in this R&D activity. The test data that will go into the data base should include results from testing conducted at the extremes of the ranges of operating conditions that a casting may encounter; current tests yield data from operation at nominal conditions This will yield a statistical distribution of results that will facilitate casting design, improve the performance of cast products, and encourage the selection of castings over products made with competing processes.

As shown in Exhibit 3-5, the development of "data-driven" relationships between chemistries, properties, and processes in the mid term will feed into the "theory-driven" data base in the long term. Associated with both of these R&D activities is the creation of a casting design book that relates materials properties and types of tests with expected cast part performance. In addition, the creation of a materials property "virtual laboratory" has been proposed as a long-term R&D activity. Based on a product and its intended application, the "laboratory" would determine the necessary materials properties, perform measurements, and disseminate the information.

The "utopic" system that would evolve from the proposed material property R&D would provide the designer with custom-made alloys for each specific application. This system would allow the designer to specify the expected conditions and desired properties for a given casting, and get a computer printout of the exact composition of the ideal alloys required for that casting.

All of the proposed R&D needs in the **materials processing** category are considered mid- or long-term needs. A very high priority in this area is the development of a clean melting and remelting process. Melting and casting processes that minimize the number of processing steps required (thereby minimizing chemistry variations) are another priority. One method of minimizing these processes would be the development of in-situ methods for melting and casting metals. There is also a need to examine emerging casting technologies, particularly semi-solid casting processes, and their effect on material properties. The goal of this effort would be to identify viable methods of controlling the material properties during processing. A long-term R&D need related to casting processes is the development of property-driven, designer-oriented foundry processes.

The **materials quality** R&D needs identified by the industry are distributed fairly evenly among the near, mid, and long term. In the near term, R&D should focus on assessing available techniques for measuring melt quality and determining its relationship to part quality. There is also a need for improved processes to characterize porosity defects.

The industry places a high priority on developing improved techniques to measure the acceptability of liquid metal prior to casting in the next 3 to 10 years. New, innovative techniques for non-destructive evaluation and testing of castings are also needed. In order to enhance the recyclability of castings without compromising the quality of products made from recycled metal, methods are needed to negate deleterious effects of unwanted secondary elements.

In the long term, additional methods for fast, accurate, non-destructive evaluation are needed to measure chemistries and material properties *after* melting and casting. These methods should expand on the mid-term R&D by extending their applicability to the input metal (ingot) and the actual cast product. Measurement of as-cast chemistries and properties will ultimately improve the integrity of cast products and allow them to meet tighter specifications, enhancing their attractiveness to designers.

The R&D needs identified in the area of **new materials** include a single near-term activity, an examination of novel alloys (for example, rare earth elements in aluminum alloys) to determine the effect that adding different components has on properties such as strength and ductility. In the mid term, corrosion- and creep-resistant magnesium alloys should be developed. These alloys would enhance the application of castings in the automobile and other markets.

Two related activities that would ensure that the metalcasting industry is not left out of the composite market are:

- the development of low-cost, castable composite materials uniquely engineered for wear-resistance, stiffness, or other properties

- the development of new materials that have properties comparable to composites

A high priority need in the **communications** area is the development of a national initiative to foster interest in materials science and engineering. Another idea is the development of web-based data bases (focusing on material interactions as well as other data) that would make critical data easily accessible by interested parties.

Other suggested near-term activities include a market study of designers' needs to help determine what types of information should be developed and made available; improved methods of facilitating communication among industrial partners, involving teleconferencing and use of the Internet, among others; and the possibility of having the American Foundrymen's Society hire an expert designer(s) who would be available to advise less experienced industry designers.

Potential Government Role

The R&D activity considered most appropriate for government co-funding is the long-term component of the development of quantitative relationships between alloys chemistries, properties, and processing (theory-driven). The mid-term component of this activity (develop relationships based on existing data) has also received significant attention in terms of appropriateness for government funding.

Other R&D needs that have been singled out by industry for their appropriateness for government co-funding included the development of a "virtual laboratory" for material properties, the development of a national initiative to foster interest in materials science and engineering, and the development of web-based data bases related to castings.